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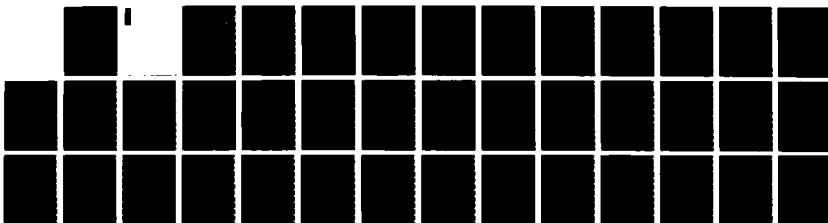
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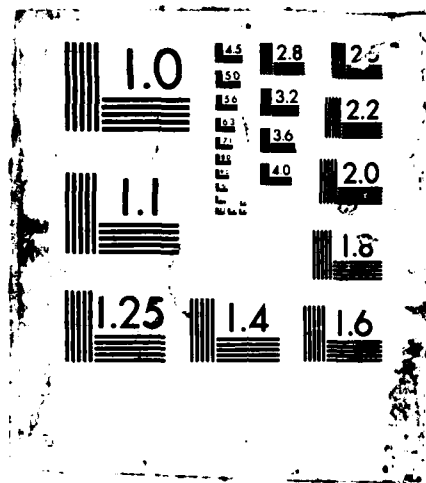
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AUTOMATIC PATTERN RECOGNITION & RELATED TOPICS

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ABSTRACT

Research in the field of opto-electronic systems research is summarized for the contract period September 1983 to September 1986. The goal has been to contribute solutions to problems of basic research importance which also have an underlying significance in systems for automatic pattern recognition, electronic imaging, and remote sensing. In theoretical and experimental research, excellent progress is reported in five major topic areas. Abstracts of publications and brief overview remarks are included on each of the following subjects: Image Retrieval, Holographic Optical Elements, Transforms in Incoherent Illumination, Diffraction Theory, and Speckle.

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AUTOMATIC PATTERN RECOGNITION & RELATED TOPICS

I. INTRODUCTION

This report contains a description of the basic research activities of the Principal Investigator, Dr. Nicholas George, Professor of Optics, and a group of doctoral scholars under Contract No. DAAG29-83-K-0166. The period covered is 19 September 1983 to 18 September 1986. The research described was supported in part by the U. S. Army Research Office. The Scientific Program Managers were Dr. Robert Lontz and Dr. B.D. Guenther.

Section II contains a description of the research findings. Section III is a listing of Presentations and Publications and Sec. IV describes related contract support. The list of Professional Staff is included in Sec. V, together with a listing of degrees granted.

II. SCIENTIFIC PROGRAM

In this portion of the final report, we describe the main findings of our research. First in Sec. II 1 we present a family tree of automatic pattern recognition, since it provides a convenient format for understanding the close relationship between various topics which we have studied. References to our publications in the open literature are preceded with the following square bracket notation: [item number, year]. By referring to the chronological listing in Section III. List of Publications, one can find the complete literature citation, paper title, and authors compiled for each year of the subject contract. Separate grouping is made of Presentations and (actual) Publications as is customary.

In Sec. II 2 we describe the results of a particularly productive research effort. We have devised a new method for obtaining spatial optical transforms in spatially incoherent illumination and without the use of an incoherent-to-coherent convertor. This research including conception, computer simulation, and finally optical hardware has led to an opto-electronic hybrid that has enormous system potential.

In Sec. II 3 we describe an important new method of image retrieval using partial information in the Fresnel-zone region. This research, so far, includes theory and computer simulation. It is interesting to point out that essentially all of the image retrieval effort in the literature (including our own) is implicitly limited to a coherent optical processor configuration. Our prediction (and proposal) is that image retrieval studies need to be extended to the case of incoherent illumination.

In Sec. II 4 we describe our research on holographic optical elements. A comprehensive system for computer-aided design has been completed using thin-grating-decomposition as a basis. Theory and experiments have been applied to the study of the spectral wavelength behavior of transmission-type holograms. We find that certain exotic lens designs can only be realized with the use of hologram and glass-lens combinations.

In Sec. II 5 we describe several separate investigations including (1) Diffraction by elliptical apertures, dielectric and conducting cylinders, and tiny square apertures; (2) Speckle from serrated circular apertures; and (3) Speckle from a cascade of diffusers.

In Sec. III we provide chronological listings of Presentations and Publications. Finally, in Sec. V, a complete listing of Scientific Personnel is provided. During the period of this contract, one M.S. (thesis) has been granted and three Ph.D. degrees.

1. SYSTEMS OVERVIEW OF OPTICAL PATTERN RECOGNITION

In our research effort is centered on automatic pattern recognition using either coherent or incoherent illumination. Related research topics of a basic nature in speckle and image understanding are also being studied. While these problems about noise and the limits of resolution typically arise from our studies of various opto-electronic systems, it is appropriate to separate them somewhat so that they can be studied in a more abstract and basic manner. Two relevant themes underlie our interest in the research being pursued. These are:

- Robot vision systems using opto-electronic hybrids
- Noise limitations in remote optical sensors.

In the following paragraphs the field of optical pattern recognition is briefly traced in order to develop a systems context for our research accomplishments.

Suppose that we have some imagery which we wish to recognize automatically or in an operator-independent fashion. This is a general problem in robot vision. Approaches to this general problem in pattern recognition can be classified according to the tree structure shown in Fig. 1.1. One can choose a direct computer method in which the input object is imaged via a detector array into a digital computer or alternatively one may elect a transform method. Since the type of equipment varies greatly with these two approaches, it is helpful at the outset to decide which is the more appropriate. This matter has been studied by us and by others in prior years, and it is generally agreed that the domain which permits one to sample coarsely and still to make recognition decisions to an acceptable accuracy is the more appropriate. For example, in facial recognition a coarse sampling of

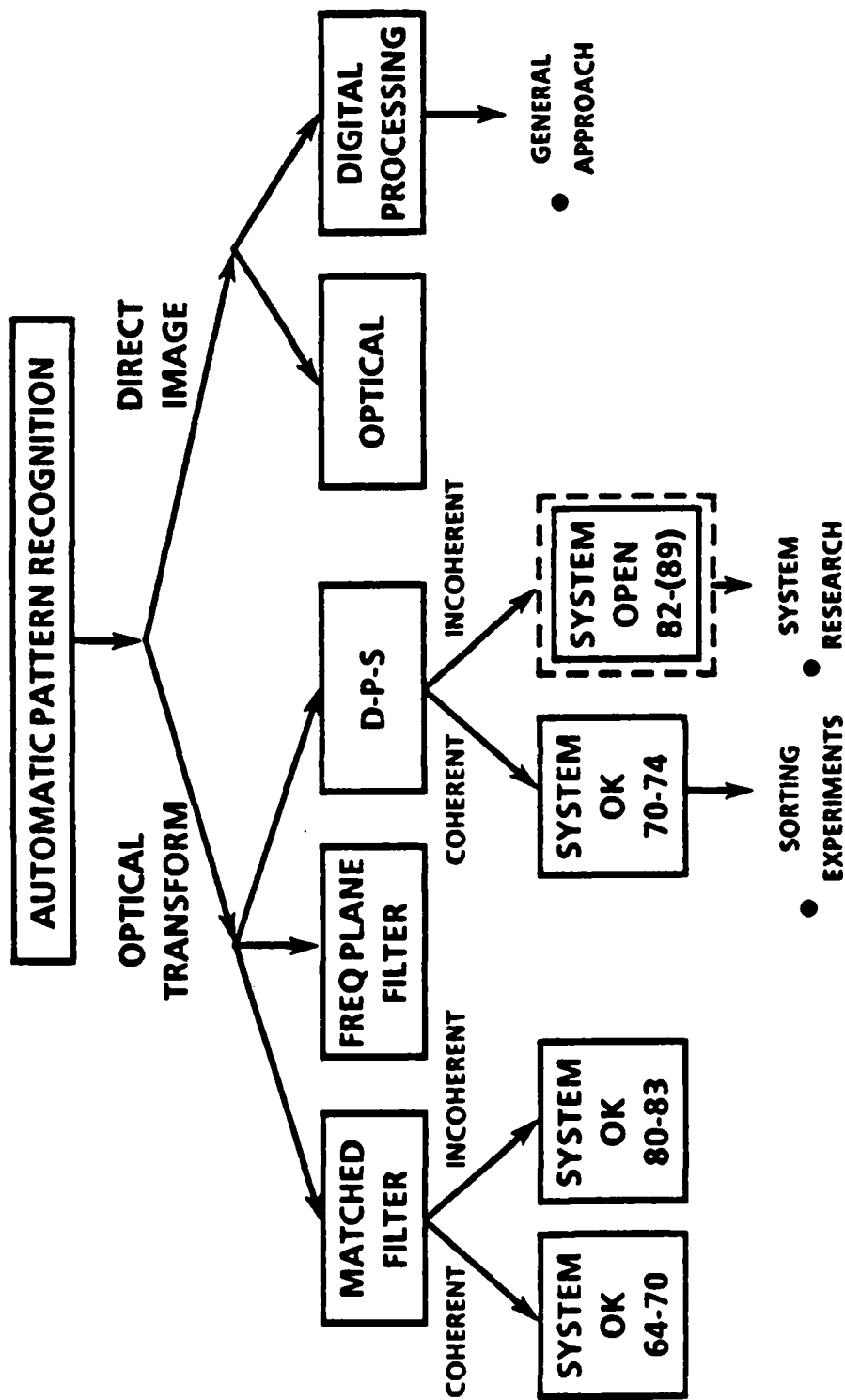


FIG. 1.1. Family tree showing main approaches in automatic pattern recognition: direct image processing or optical transform preprocessing. Optical transform methods are advantageous when the frame rate and the pixels per frame are high. In our systems research, we are studying a new method of diffraction pattern sampling (D-P-S) in spatially and temporally incoherent illumination. Separately, sorting and classification topics are being pursued using digital image processing and D-P-S in coherent illumination.

the direct image, say with 200 to 1,000 pixels, is adequate. Thus, direct processing of a sampled image using a digital computer is a reasonable approach.

Alternatively, the optical transform method is preferable when imagery of larger space-bandwidth and high frame rate needs to be sorted. Aerial reconnaissance photographs are representative of this case, particularly when one wants to make a simple assessment such as to count numbers of vehicles in a complex frame or to decide in an operator-independent manner whether or not a frame is cloud-obscured. Likewise automatic quality assessment, largely independent of scene content, is probably best accomplished using an optical transform method. Another futuristic and important application of opto-electronic processing is in automatic course guidance or map matching. Again the pixel number and frame rate are too high for conventional processing.

In our research we are particularly interested in pattern recognition when large numbers of pixels are involved, hence in the optical transform approach. It is important to state this qualification explicitly. Then in reviewing our studies of optical transform systems, one can readily understand our emphasis on systems that will work to diffraction limits. Inherently these will be capable of working with high resolution imagery or detailed objects. On the other hand, the geometrical optics class of transform devices probably are not suitable for pattern recognition of detailed objects or high resolution imagery.

Research on optical transform methods during the past twenty years centered first on systems using coherent (laser) illumination. Both matched

filtering systems and then later diffraction pattern sampling (DPS) received much attention. In a research sense specific systems matured approximately in 1970 and 1974, respectively, as shown by the OK label in Fig. 1.1.

Then as far as system research, interest shifted toward optical processing in white light. In our research during the period 1980-86, we have studied, successively, matched-filtering and now diffraction-pattern-sampling in illumination that is both spatially incoherent and temporally broadband. A very successful reduction to practice of the matched-filtering program was achieved during the 1980-83 period, under joint sponsorship by ARO and AFOSR. Noteworthy achievements were (1) Fourier transform achromats and (2) the concept of achromatic optical processors.

Our research in DPS using incoherent illumination is extremely active now; and as we forecast, this activity will continue for 3 or more years. As the reader is probably aware, making DPS work in incoherent illumination is much more complicated than simply changing the source in the coherent system. At the start of this 1983-86 period of research being reported herein, we had just reported on the first diffraction-based spatial cosinusoidal transform device¹ and the subsequent research contributions are summarized in Sec. II 2. below.

In this program of research sponsored by ARO, the concept of a diffraction-based spatial cosinusoidal transform was advanced and then reduced to practice. A novel opto-electronic hybrid is presently being studied, and many

¹ Nicholas George and Shen-ge Wang, "Cosinusoidal Transforms in White Light," Appl. Opt. 23, 787-797, 1984.

interesting results are being obtained. These are described in the following section of this report.

2. TRANSFORMS IN INCOHERENT ILLUMINATION

Statement of the Problem and Summary of Accomplishments

In this research our main objective is to conceive and demonstrate novel methods for obtaining spatial optical transforms for 3-dimensional objects in natural illumination. An effective optical transform system would pave the way for the realization of practical systems for diffraction-pattern-sampling in incoherent illumination. This type of system would represent a major achievement in optical or vision portions of robotics and it would have widespread uses in production automation and in DoD.

Prior to the start of this contract, a review paper which described our earlier efforts on matched filtering in incoherent illumination [6-1983] was published. This research in collaboration with G. Michael Morris had led to the concept and demonstration of Fourier transform achromats, as well as to state-of-the-art matched filter correlation in broadband illumination. However, with the start of the subject contract we redirected our main effort toward a white-light, diffraction-pattern-sampling system, recognizing that an opto-electronic hybrid would likely result in a more versatile system. A major first-step was the conception and demonstration of a diffraction-limited optical transform configuration [5-1984]. As described in the referenced publication, a novel passive system was demonstrated for taking spatial sine or cosine optical transforms without the need for an incoherent-to-coherent converter.

Many advancements were made in the theory of optical transforms in white light that is both spatially and temporally incoherent, as described in presentations [2-1985, 4-1986, 7-1986] and in publications [10-1985] including a comprehensive doctoral thesis by Shen-ge Wang [13-1986]. This research is continuing at a fast pace.

2.1 Selected Abstracts

A listing of presentations and publications is contained in Sec. III. These are indicated by square brackets, which include a numerical listing within each year followed by the year, e.g., [5-1984]. In this section we have grouped selected abstracts which relate to optical transforms, and these are reproduced in their entirety so that one can gain some impression of the chronology of events on each topic. We cover the contract period from September 1983 to September 1986.

Optical transform systems that will work well with broadband, spatially incoherent illumination are attractive in hybrid processor applications, particularly if they have a large space-bandwidth product. Systems based on

diffraction theory considerations can be made to meet these requirements. In this paper we describe the synthesis of a cosinusoidal (2-D spatial cosine or sine transform of intensity with bias) transform system including its interface to a digital computer. The Abstract of a paper published in *Applied Optics* 23, 787-797 (1984) follows:

[5-1984] Appl. Opt. 23, 787-797 (1984)

Cosinusoidal Transforms in White Light

Nicholas George and Shen-ge Wang

Theory and techniques of white light interferometry have been studied to devise an opto-electronic hybrid for diffraction pattern sampling. For an incoherently illuminated input scene, we obtain an output intensity that is the 2-D spatial cosine transform of the input plus a bias term. The bias can be subtracted electronically to within shot noise fluctuation limitations. The optical system consists of a double-imaging interferometer with a beam-splitter cube and crossed right-angle-prism reflectors followed by an achromatic-optical-transform lens pair. A photodiode array is placed in the optical transform plane, and this is coupled to a digital computer for further signal processing. Theoretical results are presented for the synthesis of the cosinusoidal transform configuration. From Fresnel-zone theory, a general form is derived for the impulse response of a cascade of ideal thin lenses, and this is used to design Fourier transform achromats that are well suited to this application. Experiments are presented showing cosine transforms for rough objects and for objects in reflection using illumination of negligible spatial coherence at the object. Excellent sensitivity is obtained with the bias subtraction, and a high space-bandwidth product is attained for the system.

An abstract of a talk at the Optical Society of America is presented next, followed by a paper which was published in *Applied Optics*.

[2-1985] J. Opt. Soc. Amer. A 2(13), P20 (1985)

Transforms, Correlation, and Image Reconstruction in Incoherent Illumination

Shen-ge Wang and Nicholas George

Optical transforms of 2-D and 3-D objects taken in spatially incoherent broadband illumination are described. Two optical systems are compared: one is a lensless Fresnel-zone system and the other uses a Fourier achromat. Both are opto-electronic hybrids with a twin-imaging interferometer, a CCD array, and an output digital computer. Diffraction-limited performance is obtained and a variety of transforms including 2-D spatial sine,

cosine, Fresnel, and Hartley are discussed. Also we describe a series of correlation experiments in which an optical transform and a computer-stored transform are multiplied and inverted. In this manner objects correlated include fingerprints on opaque cards, actual rough currency, and 3-D models. In a separate group of experiments image reconstructions were obtained. First, a computer method is used to invert the optical transform after bias removal and filtering, and the image reconstruction is displayed on a video terminal. This gives us an excellent means of measuring our overall space-bandwidth product. Second, image reconstruction using a cascade of two twin imaging interferometers is also described. Interesting optical processor applications for this two-stage system are briefly described.

[10-1985] Appl. Opt. 24, 842-850 (1985)

**Fresnel Zone Transforms in Spatially
Incoherent Illumination**

Shen-ge Wang and Nicholas George

Two-dimensional sine, cosine, and Fourier transforms are obtained for objects illuminated by spatially incoherent, bandlimited light. A lensless Fresnel zone processor consisting of a double-imaging interferometer, a CCD array, and a digital computer is described and analyzed. Excellent bias removal and shot-noise level performance are obtained using a 14-bit digitizer. Experimental optical transforms are presented for an offset circular aperture and for a binary zone plate transmittance. The space-bandwidth product is derived, and excellent comparison with experiment is obtained.

A comprehensive study of the theory and practice of transforms in white light is contained in the doctoral thesis of Shen-ge Wang. The Abstract is reproduced below, as follows:

[13-1986]

Optical Transforms in White Light

Shen-ge Wang

An opto-electronic hybrid has been developed for implementation of optical transforms in natural light. Specifically, a two-dimensional cosine, sine, or Hartley transform plus a bias term is obtained interferometrically from an intensity-distributed object under spatially incoherent broadband illumination. The bias term can be subtracted electronically within shot noise fluctuation limitations. The hybrid system consists of a double-imaging interferometer with a beam splitter and crossed right-angle-prism reflectors, an achromatic transform lens pair, a 2-D CCD array and a digital computer.

A close relationship has been shown between the system-possessed space-bandwidth product and the spatial and temporal coherence of illumination. Theoretical investigations are presented, showing the capabilities and limitations of the system. Requirements on both spatial and temporal aspects are derived, which enable our designing of the optical system for a diffraction-limited performance.

Experiments are presented showing optical transforms of 2-D and 3-D objects. Excellent sensitivity is obtained with the bias subtraction, and a high space-bandwidth product is in a good agreement with theoretical predictions. Applications of cosinusoidal transforms for correlation experiments and image reconstructions are also demonstrated.

3. IMAGE RETRIEVAL

Statement of the Problem and Summary of Accomplishments

Others have shown that images can be retrieved from partial information about the spatial Fourier transform. For this contract period, the problems we posed are (1) Can the image be retrieved from amplitude-only data in the Fresnel-zone region? and (2) Again in the Fresnel-zone, can one retrieve images using phase-only data? Our research marks the first treatment of image retrieval using information away from the Fourier domain, i.e., in the more general Fresnel-zone region. Also it has a direct relevance in actual system considerations and in image understanding. We started with a fairly general consideration studying the importance of phase in the Fourier transform domain [2-1984] and followed this with definitive answers (yes) to the two questions above in talks [3,4-1985; 3-1986] and in an important publication [8-1986] that was featured on the cover of *Applied Optics*. This research is computer-intensive and extensive specialized software has been developed to complement two mainframe MASSCOMP Computers which have been purchased for this research using funding provided by the New York State Science and Technology Foundation.

In 1986 two separate developments are interesting to report. First, we were successful in developing a theoretical explanation for the amplitude-only retrieval in the Fresnel-zone region that provided an understanding of the rapid converge of the output image from amplitude-only data [9-1986]. Secondly late in 1986, we formulated a significant, different problem in image retrieval; and currently we are studying this connection between image retrieval and electronic imaging with an emphasis on incoherent illumination. No publications are available on this new problem. This research is continuing.

3.1 Selected Abstracts

Image retrieval is an important new area of research in image understanding that arose out of the studies of Fienup who showed that amplitude-only data could be used to compute iteratively and recover the original image.^{1,2} This research led to much activity at various laboratories. One of the more interesting next steps was that of Hayes, Lim, and Oppenheim (1980) who

¹ J.R. Fienup, "Reconstruction of an object from the modulus of its Fourier Transform," *Opt. Lett.* **3**, 27-29 (1978).

² J.R. Fienup, "Phase Retrieval in Astronomy," in *Digest of the Topical Meeting on Signal Recovery and Synthesis with Incomplete Information and Partial Constraints* (Optical Society of America, Washington, D.C., 1983).

showed even higher quality image retrieval using phase-only data in the Fourier domain.^{3,4}

In our research supported by the U.S. Army Research Office, we present a method for reconstruction of an image from partial data in the Fresnel zone region. As we demonstrate using computer simulations, it is possible to obtain excellent image reconstructions using either phase-only or magnitude-only data from the Fresnel zone transform of a real-valued object. A novel aspect of this work is in the reconstruction of an image from data in the Fresnel zone.

It is shown that for this type of reconstruction, as we move away from the Fourier plane, we obtain very good reconstructions in just a few iterations from phase-only information. The image quality does not vary much with position. However, for the same number of iterations, reconstructions from magnitude information improve markedly as we move farther from the Fourier plane. This is an interesting and unanticipated finding.

We present the following Abstract of our paper published in *Applied Optics*, 25, 178-183 (1986) which contains the details of our results summarized above.

³ M.H. Hayes, J.S. Lim, A.V. Oppenheim, "Signal Reconstruction from Phase or Magnitude," IEEE Trans. Acoust. Speech Signal Process. ASSP-28, 672-680 (1980).

⁴ A.V. Oppenheim, J.S. Lim, S.R. Curtis, "Signal Synthesis and Reconstruction from Partial Fourier Domain Information," J. Opt. Soc. Am. 73, 1413-1420 (1983).

[8-1986] Appl. Opt. 25, 178-183 (1986)

**Image Reconstruction from Partial
Fresnel Zone Information**

Robert Rolleston and Nicholas George

An iterative algorithm for reconstructing an image from partial Fresnel zone information is described. With the standard 4-F canonical optical processor, processing is done midway between the two lenses in the Fourier transform plane. While others have studied iterative methods of reconstruction from partial Fourier plane information, we have investigated methods of reconstructing an object from partial information in the Fresnel region of an optical processor. Iterative algorithms for reconstructing an object from either the phase or magnitude of the Fresnel zone transform are described. In the case of reconstructing an image from Fresnel zone magnitude, we obtain good images in fewer iterations at locations which are further from the Fourier plane. Reconstructing an image from the Fresnel zone phase is fairly insensitive to this shift out of the Fourier plane.

An Abstract of a talk presented to the Optical Society is also included below. Some interesting search algorithms have been studied in order to ascertain the position within the Fresnel zone in an operator independent fashion. The Abstract follows:

[3-1985] J. Opt. Soc. Amer. A 2(13), P20 (1985)

**Image Reconstruction from Partial
Fresnel Zone Information**

Robert Rolleston and Nicholas George

An iterative algorithm for reconstructing an image from partial Fresnel zone information is discussed. With the standard 4-F canonical optical processor, processing is done midway between the two lenses in the Fourier transform plane. While others have studied reconstruction from partial Fourier plane information, we have investigated methods of reconstructing an object from partial information in the Fresnel region of an optical processor. Efficient digital calculation for integrations with a Fresnel-zone type of kernel are described. Iterative algorithms for reconstructing an object from either the phase or magnitude of the Fresnel zone transform are discussed. In the case of reconstructing an image from the Fresnel zone magnitude, we obtain good images in fewer iterations at locations which are

farther from the Fourier plane. Reconstructing an image from the Fresnel zone phase is fairly insensitive to this shift out of the Fourier plane. In another investigation, we start with the assumption that the object has been coded into an unknown location in the Fresnel region. We describe an iterative searching technique that locates this position; thereafter we reconstruct the image.

Our most recent publication on image retrieval is the theoretical deduction that reconstructions from amplitude-only data will be of better image quality at fixed number of iterations the farther one is from the Fourier transform plane. This paper is published in the *Journal of the Optical Society of America, Series A* and is reproduced as follows:

[9-1986] J. Opt. Soc. Am. A 4(April), xxx-yyy (1987)

**Stationary Phase Approximations in Fresnel-Zone
Magnitude-Only Reconstructions**

Robert Rolleston and Nicholas George

An analytic approximation of an iterative method of image reconstruction from Fresnel-zone magnitude data is discussed. The method of stationary phase is used to estimate both the Fresnel-zone transform and the inverse Fresnel-zone transform. With this theory we can explain why fewer iterations are needed for good images to be obtained at locations in the Fresnel-zone region of an optical processor that are farther from the Fourier-transform plane.

4. HOLOGRAPHIC OPTICAL ELEMENTS

Statement of the Problem and Summary of Accomplishments

Holographic optical elements possess tremendous potential in solving very specific problems which previously have been insurmountable or only awkwardly remedied. Both the Fourier achromat and the head-up display are practical examples which illustrate this potential. In our long-range program of holographic research, we have targeted basic theoretical problems in several areas of holographic elements, including: 1) analysis of transmission-type lens elements; 2) very high numerical aperture effects; 3) high dispersion laser optics; 4) aberration compensation optics; 5) broad spectrum holographic systems; and 6) corresponding topics with multilayer reflective elements.

The main results during the contract period are a digital computer program for the computation of performance of an arbitrary transmission hologram optical element. Descriptions of this program and illustrative optical system designs have been made at various meetings [3,4-1983] and [1-1984]. With our fairly unique specialty of hologram optical elements that work over a broad wavelength band as a theme, we published a comprehensive analysis of the wavelength performance of transmission elements [8-1985]. A definitive treatment of efficiency and bandwidth was also completed with the publication of a doctoral thesis by Thomas W. Stone [12-1986].

4.1 Selected Abstracts

During the 1983-86 contract period, we have completed our studies of the diffraction theory analysis of arbitrary transmission type elements. In our studies we have found that two separate analyses are generally useful in the innovation and design of useful elements. One analysis is a phased-array, scatterer theory (approximate), and the other is an improved method of thin grating decomposition. The former is preferable for developing a quick theoretical understanding of angle or wavelength detuning, Bragg resonance, and so on. The latter is preferable in a detailed analysis of some configuration when accuracy is important. The Abstracts of the more important publications which were made during the contract period are included below.

[8-1985] Appl. Opt. 24, 3797-3810 (1985)

**Wavelength Performance of Holographic
Optical Elements**

Thomas Stone and Nicholas George

A comprehensive treatment is presented for the diffraction efficiencies of transmission holographic elements and cascade lenses when subject to broad spectral and field angle detunings. Experimental measurements are made in support of our theory on holographic optical elements fabricated in bleached silver-halide emulsions and in dichromated gelatin. The theory of holographic grating diffraction efficiency is studied through two approaches. A numerical treatment based on the theory of thin grating decomposition is implemented and shown to be in close agreement with other theories. Additionally, a more approximate approach is pursued in which the volume grating is treated as a phased array of scatterers. The latter approach leads to closed-form formulas in addition to a simple physical picture of volume effects. It is found that three-element cascades can exhibit spectral and field angle bandwidths essentially as broad as two-element cascades and that these bandwidths are in excess of 2300 Å and 7° respectively.

[12-1986]

Holographic Optical Elements

Thomas W. Stone

A comprehensive treatment is presented for the diffraction efficiencies of transmission holographic elements and cascade lenses when subject to broad spectral and field-angle detunings. Experimental measurements and verifications are made on holographic optical elements. The theory of holographic grating diffraction efficiency is studied through two approaches. A numerical treatment based on the theory of thin grating decomposition is pursued in which the volume grating is treated as a phased array of scatterers. The latter approach leads to closed-form formulas in addition to a simple physical picture of volume effects. Extensive parametrical studies are presented for the properties of volume holographic elements. It is found that three-element cascades can exhibit spectral and field angle bandwidths essentially as broad as two-element cascades; that these bandwidths are in excess of 2300 Å and 7° respectively; and that these can more than double with specialized techniques presented. Applications of holographic elements to imaging are presented and a paraxial chromatic thickness aberration is discussed.

5. DIFFRACTION THEORY AND SPECKLE

Statement of the Problem and Summary of Accomplishments

Topics collected in this section relate to remote sensing or are of a more abstract, theoretical nature. They are briefly described in Sections 5.1 to 5.3 below.

5.1 Diffraction Theory

A Master of Science thesis was completed by Paul Kane in which diffraction pattern sampling was studied as a means for rapidly and remotely sensing the size and the eccentricity of elliptical holes in conducting sheets. The Abstract of this thesis is presented as follows:

[6-1984]

Diffraction by Elliptical Apertures: Theory and Experiment

Paul J. Kane

Diffraction by elliptical apertures is studied in theory and experiment. The far zone diffraction pattern of the elliptical aperture is obtained, based on scalar diffraction theory. The results of this analysis show excellent qualitative agreement with diffraction patterns observed in the laboratory. Two separate algorithms are considered for the measurement of aperture dimensions, based on the diffraction pattern data. For the aperture sizes under consideration, an algorithm based on a single pattern data point (the first secondary maximum) shows the best absolute accuracy. A second algorithm, based on cross sectional samples of the pattern, exhibits the best consistency. The calculation of aperture eccentricity from the aperture width data is also considered. As a separate study, a system is described which allows the far zone diffraction patterns of individual ellipsoidal particles to be examined.

A comprehensive study of light scattered by large dielectric cylinders was completed during the contract period by M.A.G. Abushagur. A comparative study was also made contrasting the scattering patterns due to dielectric and conducting cylinders of the same diameter. A central finding of this study is that one can readily separate cylinders remotely depending upon whether they are dielectric or conducting. An Abstract of this doctoral thesis is reprinted, as follows:

[7-1984]

Scattering of Light From Large Cylinders

Mustafa A.G. Abushagur

Scattering of a plane electromagnetic wave from circular conducting and dielectric cylinders is analyzed. Both polarizations of the incident electric field, parallel and normal to the axis of the cylinder, are considered. The study of the rigorous solutions gives an insightful understanding of the scattered field and its dependence on the material of the cylinder, the polarizations of the incident field, and the three dimensionality of the object which usually are not considered in Fourier optics. It is shown that a combination of Fourier optics and ray theory can give good approximations for the scattered field from both conducting and dielectric cylinders. It is shown that the scattered pattern from a conducting cylinder consists of a main lobe and a number of side lobes. The spacing between the side lobes decreases as ka increases, where k is the wave number of the incident field and a , is the radius of the cylinder. It is found that for a certain conducting cylinder the side lobes terminate in a smaller scattering angle when the incident field is polarized parallel to the axis than when the incident field is polarized normal to the axis of the cylinder. The surface current density in the shadow region is found to be larger for the normal polarization case than for the parallel polarization case. The pattern of the scattered field from a dielectric cylinder has fringes all around the cylinder. The contrast of the fringes for the dielectric cylinder is much larger when the polarization of the incident field is parallel to the axis than that when the polarization is normal to the axis. The backscattered field of the dielectric cylinder has a peak which depends in its position on the refractive-index of the cylinder for the parallel polarization case. The fine structure of the scattering by a dielectric cylinder is studied. It is shown that the dielectric cylinder has resonant frequencies which depend on the radius and refractive-index of the cylinder. It is found that there are significant differences in the shape of the scattered pattern depending on whether the cylinder is at-resonance or at off-resonance. Experimental investigations are carried out to verify the theory derived in this study and it is found that both theory and experiments are in good agreement.

Dr. Abushagur completed his doctoral studies with the Principal Investigator, Nicholas George, and then he accepted an appointment as an Assistant Professor of Electrical Engineering at the University of Alabama. The following publication of a portion of his doctoral studies appeared in *Applied Optics* in 1985, and the Abstract is presented, as follows:

[9-1985] Appl. Opt. 24, 4141-4145 (1985)

**Polarization and Wavelength Effects on the
Scattering from Dielectric Cylinders**

M.A.G. Abushagur and Nicholas George

The scattered intensity patterns of large dielectric cylinders ($ka \approx 1000$) are studied using the exact solution for the case of normal incidence. The two different polarizations of the incident electric field, parallel and normal to the axis of the cylinder, are considered. A comparison between the scattered patterns of the two polarizations is presented. The fine structure of the scattering pattern is also presented. It is shown that the scattered intensity has resonances as the wavelength is scanned. An experimental investigation is carried out to illustrate the theory, and good agreement between theory and experiment is achieved.

A diffraction theory topic of fundamental importance to sub-resolution in microscopy (or in remote sensing) is the radiation pattern of tiny objects. For example, the exact distribution of fields in a circular aperture (in a perfectly conducting sheet) has been obtained by Bethe (1944) and corrected by Bouwkamp (1954). However, no one has been able to write an explicit, rigorous solution for the radiation field of a tiny square aperture in a perfectly conducting sheet. During a portion of this contract period, R. Edward English, Jr. has written a doctoral proposal outlining studies of this topic [6-1985]. In 1986 a manuscript was submitted for review to the *Journal of the Optical Society of America, Series A*. This article is presently in review; and the Abstract outlining the solution of this basic problem is provided, as follows:

[10-1986]

**Approximate Aperture Fields for a
Small Square Aperture**

R. Edward English, Jr. and Nicholas George

An approximate solution for the aperture electric field in a single, small square aperture ($2a$ by $2a$, $ka \ll 1$) in a thin, perfectly conducting plane screen illuminated by a normally incident, linear polarized plane wave is presented. Copson's integro-differential equation formulation of the boundary value

problem applied to small apertures is used to investigate the validity of the solution. Numerical calculations show that the solution is valid over most of the aperture; its validity is in doubt in the close vicinity of the corners of the aperture.

In a separate diffraction theory problem, R. Edward English, Jr. considered orthogonal expansions for arbitrary input objects in forms particularly suited to propagation calculations. Some very interesting Hermite- and Laguerre-Gaussian beam modes were considered. The first preliminary results of this research were presented in a talk at the 1986 Annual Meeting of the Optical Society of America [1-1986]. An Abstract of this talk is reproduced below, as follows:

[1-1986] J. Opt. Soc. Am. A 3(13), P115 (1986)

**Diffraction Under Gaussian Illumination:
A Gaussian Beam Expansion Approach**

R. Edward English, Jr. and Nicholas George

A conventional approach to solving diffraction problems involves integrating an input field multiplied by the Fresnel diffraction kernel. Alternately, one can solve the associated differential equation subject to certain boundary conditions. The Hermite- and Laguerre-Gaussian beam modes are complete and orthogonal sets of functions for this differential equation suited, respectively, for Cartesian and cylindrical geometries. Proceeding in this way, we describe a Gaussian beam expansion approach that is suitable for solving certain diffraction problems.

We present analytic and numeric calculations from this approach applied to some illustrative diffraction problems. Some experimental results are also presented.

Another research topic is being studied that combines scattering and automatic pattern recognition. In studying whether or not one can remotely sense some characteristic of a class of objects, it is necessary to have a very good understanding of the optical transform pattern. We would like to be able to distinguish coated spherical globules or coated cylinders remotely. For example, with a metallic cylinder coated with a dielectric, we would like to be able to sense remotely the respective diameters and the index-of-

refraction of the cladding. Scott D. Coston is the doctoral scholar who is studying this topic. He has written a formal thesis proposal on this subject [7-1985]. The Abstract is reprinted below, as follows:

[7-1985]

**Light Scattering from Stratified Spherical Particles
With Emphasis on Particulate Sizing**

Scott D. Coston

In the proposed research, light scattered from a stratified sphere composed of a dielectric-coated metal is studied. We will study the dependence of the scattered light on the wavelength and on the descriptive parameters of the scatterer. Special attention is given to scattering at resonance. Approximations to the exact theory for light scattering from a thinly coated and a small core stratified sphere will be derived and tested. This research has applications in atmospheric studies, space sciences, and biological studies.

5.2 Speckle from Serrated Circular Apertures

An important factor in the study of pattern recognition and image quality is edge quality. Granularity, a major factor in the measure of image quality, may be manifested in serrated edges. Studying the optical Fourier transform of serrated edges is an appropriate method of analysis, since the serration represents the addition of high-frequency detail. Diffraction from straight, serrated edges and gaps has been studied earlier.¹ During the present contract period, we completed the preliminary phase of study for the case of a serrated circular aperture. The results of this study were described in a formal proposal for a doctoral thesis by Madeleine Beal [3-1984]. The Abstract of this thesis proposal is presented, as follows:

¹ Nicholas George and G.M. Morris, "Diffraction by Serrated Apertures," J. Opt. Soc. Am. 70, 6-17 (1980).

A Study of Diffraction from Serrated, Circular Apertures

Madeleine M. Beal

A study of the diffraction from serrated, circular apertures is proposed. The apertures emulate curved edges which have been degraded by image graininess, as in aerial photography; they also model apertures, pinholes, etc., used in optical systems and etched or machined holes. The problem is approached as a statistical diffraction (speckle) problem; the first- and second-order correlation functions of the intensity in the diffraction pattern are appropriate calculations. The mutual intensity, a basic quantity in these calculations, is expressed in terms of the characteristic function of the aperture's radial distribution for the case in which the roughness is large compared to the illuminating wavelength. Approximations to the scalar distribution, based on Fresnel zone theory, are suggested.

Another suitable method of analysis is digital evaluation of the diffraction integrals, since it allows simple adjustment of the system parameters; useful sets of parameters can be determined digitally before final experimental designs are completed, and theoretical and experimental results can be corroborated. Finally symmetrization, a geometrical technique based on the relationships between serrated and smooth circular apertures, is proposed as an analytical tool in the study. These several techniques are to be used to determine the relationships between edge serration and the diffraction pattern, anticipating the advantages of the diffraction pattern as a measure of the serration.

5.3 Speckle from a Cascade of Diffusers

The wavelength dependence of speckle in the light transmitted through or reflected from a diffuser has been used to determine the roughness of diffusers.¹⁻³ Information about diffusers in a cascade may also be obtainable from the speckle produced. The topic which we have posed for the contract

¹ Nicholas George and Atul Jain, "Space and Wavelength Dependence of Speckle," *Appl. Phys.* **4**, 201 (1974).

² R.D.S. Melville, "Spatial and Spectral Behavior of Speckle in an Imaging System," Ph.D. Thesis, California Institute of Technology, (1975).

³ Nicholas George, Atul Jain, and R D S Melville, "Experiments on the Space and Wavelength Dependence of Speckle," *Appl Phys* **7**, 157 (1975).

period 1983-86 is the study of the thick diffuser, as modeled by a cascade of two or more thin diffusers. This problem had not been treated, heretofore, in the literature. It is both a challenging theoretical problem in statistical optics, and a speckle problem of far-reaching systems importance for multi-bounce lidar and radar. Excellent progress has been made starting with a formal thesis proposal by a doctoral scholar Lyle G. Shirley [4-1984].

[4-1984]

Speckle from a Pair of Diffusers

Lyle G. Shirley

In the proposed research, the wavelength dependence, space dependence, and angle of illumination dependence of the speckle from a pair of diffusers will be studied to see what information about the individual diffusers and their relation to one another may be extracted. This research has important applications in remote sensing such as seeing through a diffuse surface to find information about a hidden surface. A comprehensive study of both the experimental and the theoretical aspects of speckle from a pair of diffusers is proposed.

During the early stages of this research, we completed a computer-controlled test range for measuring laser scattering patterns over a 180° sector with a dynamic range of 8 orders of magnitude. And a preliminary study of the speckle or radiation pattern from a sampling of rough surfaces was completed. There are two aspects of this first publication [1,11-1985] that should be mentioned. One is that special effort has been made to read speckle patterns over a very wide angle with a large dynamic range. Secondly, a careful effort has been made to relate the functional form of the transverse correlation coefficient of surface roughness to the far-zone radiation pattern. The Abstract of this publication is presented, as follows:

**Diffuser Transmission Functions and
Far-Zone Speckle Patterns**

Lyle G. Shirley and Nicholas George

A model for the transmission of light through a thin diffuser is presented which accounts for the angle of incidence of an input plane wave. This model is then used to make several illustrative calculations of the spectral intensity of the light scattered by the diffuser for arbitrary correlation lengths. In these calculations, it is assumed that the diffuser roughness is represented by a jointly normal random process. The spectral intensity is evaluated analytically for a triangular correlation function and arbitrary diffuser roughness. Experimental curves are also presented of the radiation patterns of ground glass for a wide range of illumination angles with the output angle θ being swept over the range $\pm 90^\circ$.

For the second phase of this research, considerable effort was expended to develop a series of diffusers with controlled characteristics. Frosted glass can be fabricated using grinding powders, sandblasting, acid-etching, or some combination of these. The microstructure of the resulting samples were inspected both with optical and electron-beam microscopy. A really excellent series of samples has been developed, but full description of these has not been prepared for publication as of the end of the contract period. Nevertheless, the smoother, acid-etched samples were used in the final phase of the research under the present contract, as described in the following paragraphs.

In the final phase of the present contract, a refined theoretical treatment was published for the thin diffuser at wide angles. A new transmission function is derived and compared to earlier approximate formulas. This publication is in the *Journal of the Optical Society of America, Series A*, and the Abstract of this paper is reproduced below, as follows:

[11-1986] J. Opt. Soc. Am. A 4(April), xxx-yyy (1987)

Wide-Angle Diffuser Transmission Functions and Far-Zone Speckle

Lyle G. Shirley and Nicholas George

Models for the transmission of light through either rough surface or bulk diffusers are presented. Since the transmission function contains a dependence upon the input angle, it is convenient to use an angular spectrum representation for the input illumination in the general case. Computer simulations of far-zone speckle patterns and analytical calculations of the ensemble averaged radiation patterns are made with and without the angle dependence in the transmission function. We find that this angular dependence is relatively unimportant with input illumination near normal incidence. However, the computer simulation demonstrates that the angle dependence can make a significant difference in the detail of the speckle pattern for a complex input spectrum or even for a single plane wave at large ($\geq 30^\circ$) angles of incidence. The essential effect of the angle dependence on the averaged radiation patterns is to increase the effective roughness of the diffuser.

Also in the final phase of the present contract, we described our analytical results for the diffuser cascade. While the results are preliminary, still excellent agreement is obtained in comparing theory and experiment. In the experiments we used our newly developed series of diffusers with carefully controlled characteristics. A presentation of theory and experiments was made at the 1986 annual meeting of the Optical Society of America [2-1986] and the Abstract is given as follows:

[2-1986] J. Opt. Soc. Am. A 3(13), P121 (1986)

Speckle from a Thick Diffuser

Lyle G. Shirley and Nicholas George

We describe the speckle pattern caused by a thick diffuser including a study of decorrelation effects with angle of illumination and wavelength. In the theoretical analysis, the thick diffuser is modeled as a cascade of two idealized thin diffusers separated by a distance z_0 . We first consider the general case of speckle from an arbitrary optical system at the output of the diffuser and then specialize to the important case of far-zone speckle. For an idealized thin diffuser, i.e., modeled by a transmission function $t(x,y)$, the far-zone pattern moves as a whole and is centered along the axis of the illumination.

However, for the thick diffuser, the detail of the speckle pattern also begins to decorrelate as the shift in angle $\Delta\theta$ increases. We show that in the far-zone case there is a simple relationship between the separation z_0 and the shift $\Delta\theta$ required for decorrelation of the speckle pattern.

Experimental results are also presented which illustrate the decorrelation of far-zone speckle patterns with increasing angle of incidence about the normal for a pair of diffusers with controlled separation z_0 . The experiments are compared to the theoretical predictions.

This research is being continued.

III. LIST OF PUBLICATIONS

In this section we list **Presentations** and technical reports such as thesis proposals and separately we list **Publications** including journal articles and completed theses. These are listed by year for convenience. We also include a final list for the year 1983 which updates our earlier report on a prior contract which covered the 1980 to 1983 period, since these data were not finalized at the time of the report.

All of the articles listed are reports of research supported in part by funds from the subject contract. A supplementary volume to this current report has been prepared which contains all of these reprints conveniently bound together. This collection of reprints is available to the interested reader simply by sending a written request to the Principal Investigator.

1983*

Presentations and Thesis Proposals

1. "Matched Filtering in White Light Illumination," Nicholas George and G.M. Morris, Advances in Optical Information Processing, January 20-21, 1983, Los Angeles, California.
2. "Cosinusoidal Transforms in White Light," Sheng-ge Wang and Nicholas George, 1983 Annual Meeting of the Optical Society of America, October 17-20, 1983, New Orleans, Louisiana, J. Opt. Soc. Am. 73, 1858 (1983).
3. "Holographic Cascade Lens," Thomas Stone and Nicholas George, 1983 Annual Meeting of the Optical Society of America, October 17-20, 1983, New Orleans, Louisiana, J. Opt. Soc. Am. 73, 1954 (1983).
4. "Bandwidth of Holographic Optical Elements," Thomas Stone, Industrial Associates Meeting, Spring 1983, Rochester, New York.
5. "Optical Transforms in White Light," Shen-ge Wang, Industrial Associates Meeting, Fall 1983, Rochester, New York.

Publications

6. "Matched Filtering in White Light Illumination," Nicholas George and G.M. Morris, Proc. Soc. Photo-Opt. Instrum. Eng. 388, 11-22 (1983).

*These publications for 1983 finalize the list previously given in the final report to ARO on a prior contract covering the 1980 to 1983 period.

Presentations and Thesis Proposals

1. "Hologram Optical Elements," Thomas Stone, Industrial Associates Meeting, Spring, 1984, Rochester, New York.
2. "The Use of Fourier Transform Phase in Pattern Recognition," Robert Rolleston (Ph.D. Proposal, University of Rochester, 1984).
3. "A Study of Diffraction from Serrated Circular Apertures," Madeleine Beal (Ph.D. Proposal, University of Rochester, 1984).
4. "Speckle from a Pair of Diffusers," L.G. Shirley (Ph.D. Proposal, University of Rochester, 1984).

Publications

5. "Cosinusoidal Transforms in White Light," Nicholas George and Shen-ge Wang, Appl. Opt. 23, 787-797 (1984).
6. "Diffraction by Elliptical Apertures: Theory and Experiment," Paul Kane (M.S. Thesis, University of Rochester, 1984).
7. "Scattering of Light from Large Cylinders," M.A.G. Abushagur (Ph.D. Thesis, California Institute of Technology, 1984).

1985

Presentations and Thesis Proposals

1. "Diffuser Transmission Functions and Far-Zone Speckle Patterns," L.G. Shirley and Nicholas George, International Conference on Speckle, August 20-23, 1985, San Diego, California.
2. "Transforms, Correlation, and Image Reconstruction in Incoherent Illumination," Shen-ge Wang and Nicholas George, 1985 Annual Meeting of the Optical Society of America, October 14-18, 1985, Washington, D.C., J. Opt. Soc. Amer. A, 2(13), P14 (1985).
3. "Image Reconstruction from Partial Fresnel Zone Information," Robert Rolleston and Nicholas George, 1985 Annual Meeting of the Optical Society of America, October 14-18, 1985, Washington, D.C., J. Opt. Soc. Amer. A, 2(13), P20 (1985).
4. "Fourier Transform Phase," Robert Rolleston, Industrial Associates Meeting, Spring 1985, Rochester, New York.
5. "Wide-Angle Far-Zone Speckle Patterns," L.G. Shirley, Industrial Associates Meeting, Fall 1985, Rochester, New York.
6. "Electromagnetic Diffraction from Apertures in Conducting Screens," R. Edward English, Jr. (Ph.D. Proposal, University of Rochester, 1985).
7. "Light Scattering from Stratified Spherical Particles with Emphasis on Particulate Sizing," Scott Coston (Ph.D. Proposal, University of Rochester, 1985).

Publications

8. "Wavelength Performance of Holographic Optical Elements," Thomas Stone and Nicholas George, Appl. Opt. 24, 3797-3810 (1985).
9. "Polarization and Wavelength Effects on the Scattering from Dielectric Cylinders," M.A.G. Abushagur and Nicholas George, Appl. Opt. 24, 4141-4145 (1985).
10. "Fresnel Zone Transforms in Spatially Incoherent Illumination," Shen-ge Wang and Nicholas George, Appl. Opt. 24, 842-850 (1985).
11. "Diffuser Transmission Functions and Far-Zone Speckle Patterns," L.G. Shirley and Nicholas George, Proc. Soc. Photo-Opt. Instrum. Eng. 556, 63-69 (1985).

Presentations and Thesis Proposals

1. "Diffraction under Gaussian Illumination: A Gaussian Beam Expansion Approach," R. Edward English and Nicholas George, 1986 Annual Meeting of the Optical Society of America, October 19-24, 1986, Seattle, Washington, J. Opt. Soc. Am. A 3(13), P115 (1986).
2. "Speckle from a Thick Diffuser," L.G. Shirley and Nicholas George, 1986 Annual Meeting of the Optical Society of America, October 19-24, 1986, Seattle, Washington, J. Opt. Soc. Am. A 3(13), P121 (1986).
3. "Image Reconstruction from Partial Transform Data," Robert Rolleston, Industrial Associates Meeting, Spring 1986, Rochester, New York.
4. "Optical Correlations with Natural Illumination," Shen-ge Wang, Industrial Associates Meeting, Spring 1986, Rochester, New York.
5. "UR Center for Opto-Electronic Systems Research," Nicholas George, Industrial Associates Meeting, Fall 1986, Rochester, New York.
6. "Radiation Properties of Partially Coherent Sources," Avshalom Gamliel (Ph.D. Proposal, University of Rochester, 1986).
7. "Optical Transforms in White Light with Applications to Pattern Recognition," Nicholas George and Shen-ge Wang, Gordon Research Conference on Holography and Optical Information Processing, January 4-9, 1987, Santa Barbara, California.

Publications

8. "Image Reconstruction from Partial Fresnel Zone Information," Robert Rolleston and Nicholas George, Appl. Opt. 25, 178-183 (1986).
9. "Stationary Phase Approximation in Fresnel-Zone Magnitude-Only Reconstructions," Robert Rolleston and Nicholas George, J. Opt. Soc. Am. A 4, 148-153 (1987).
10. "Approximate Aperture Fields for a Small Square Aperture," R. Edward English and Nicholas George, J. Opt. Soc. Am. A (in review).
11. "Wide-Angle Diffuser Transmission Functions and Far-zone Speckle," L.G. Shirley and Nicholas George, J. Opt. Soc. Am. A 4(April), xxx-yyy (1987).
12. "Holographic Optical Elements," Thomas Stone (Ph.D. Thesis, University of Rochester, 1986).
13. "Optical Transforms in White Light," Shen-ge Wang (Ph.D. Thesis, University of Rochester, 1986).

IV. RELATED RESEARCH SUPPORT

The research described in this report was supported in part by the subject contract with the U.S. Army Research Office and in part by the University of Rochester. In addition, some of the projects herein described were supported in part under a grant from the U.S. Air Force Office of Scientific Research. This joint support was requested after obtaining the prior approval of the cognizant Technical Program Officers, as set forth in the instructions for research proposals. The AFOSR grant overlapped during the initial phases of this research from 24 October 1983 to 23 October 1984 (extended to 31 January 1985).

Finally, substantial capital equipment support for this research, as well as salaries and supplies, has also been obtained in part from the New York State Science and Technology Foundation. Care has been taken to acknowledge these sponsors in the published literature which has resulted.

V. SCIENTIFIC PERSONNEL

The Principal Investigator for this research program is Dr. Nicholas George, Professor of Optics. An extremely competent staff of doctoral scholars has been available for this research, often at greatly reduced direct salary charge to the contract due to their having received independent fellowship support. The educational background and research interests of these scholars is listed in accompanying table.

LIST OF Ph.D. STUDENTS IN PROFESSOR GEORGE'S RESEARCH GROUP.

TOPIC	SCHOLAR	PRIOR DEGREE
Diffraction Theory and Optical Metrology		
Small Particles	M.A.G. Abushagur*	M.S. E.E. Cal Tech (1977)
Small Particles	S. Coston	B.S. Physics South Florida (1982)
Sub-Resolution	R.E. English	B.S. Physics Purdue (1982)
Rough Surfaces	D. Schertler	B.S. Physics Thomas More (1985)
Partial Coherence	A. Gamliel	B.S. Math and Physics Illinois (1984)
Hologram Optics	T. Stone*	M.S. Optics Rochester (1983)
White Light Processing		
Optical Transforms	S. Wang*	B.S. Mechanics ChangChun, China (1969)
Matched Filtering	K. Farr	B.S. Physics Alabama (1983)

*Degree awarded during this ARO Contract Period.

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Table continued . . .

TOPIC	SCHOLAR	PRIOR DEGREE
Speckle and Coherence Theory		
Multiple Diffusers	L. Shirley	M.S. Physics Brigham Young (1984)
Serrated Aperture	M. Beal	B.S. Physics N.Y. Inst. of Tech. (1981)
Image Understanding		
Diffraction Pattern Sampling	P. Kane*	B.S. Physics Scranton (1980)
Diffraction Pattern Sampling	D. Venable	M.S. Optics Rochester (1983)
Image Retrieval	R. Rolleston	M.S. Optics Rochester (1983)
Sensing and Recognition	B. Stossel	B.S. Physics Penn State (1985)

*Degree awarded during this ARO Contract Period.

As shown in the following listing, several scholars received degrees during the course of this ARO contract.

STUDENT	DEGREE	THESIS REFERENCE
Dr. M.A.G. Abushagur	Ph.D. 1984	[7-1984]
Dr. T.W. Stone	Ph.D. 1986	[12-1986]
Dr. S. Wang	Ph.D. 1986 (Fall)	[13-1986]
Paul Kane	M.S. 1984	[6-1984]

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